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How many motion signals can be simultaneously perceived?

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ABSTRACT

Previous research indicates that the maximum number of motion signals that can be simultaneously perceived is 2, if they are defined only by direction differences, or 3 if they also differ in speed or depth (Greenwood & Edwards, 2006b). Those previous studies used transparent, spatially-sparse stimuli. Here we investigate this motion-number perception limit using spatially-localised stimuli that drive either the standard or form-specific motion systems (Edwards, 2009). Each motion signal was defined by four signal-dots that were arranged in either a square pattern (Square Condition), to drive the form-specific system, or a random pattern (Random Condition), to drive the standard motion-system. A temporal 2AFC procedure was used with each interval (150 ms duration) containing n or $n+1$ signals. The observer had to identify the interval containing the highest number of signals. The total number of dots in each interval was kept constant by varying the number of noise dots (dots that started off in the same spatial arrangement as the signal dots but then each of those dots moved in different directions). A mask was used at the end of each motion sequence to prohibit the use of iconic memory. In the Square Condition, up to five directions could be simultaneously perceived, and only 1 in the Variable condition. Decreasing the number of noise dots improved performance for the Variable condition, and increasing it decreased performance in the Square Condition. These results show that the previously observed limit of 3 is not a universal limit for motion perception and further, that signal-to-noise limits are a fundamental factor in determining the number of directions that can be simultaneously perceived. Hence the greater sensitivity to motion of the form-specific system makes it well suited to extracting the motion of multiple moving objects.

1. Introduction

The ability to perceive motion is vital to our ability to interact with our environment, hence a great deal of research has focused on understanding how the brain processes motion information (Nishida, 2011). However, it is seldom the case that we are confronted with only a single, moving object, so the ability to perceive multiple objects is important. Far less research has focused on this aspect of motion processing. A starting point in understanding how the brain processes multiple moving objects is to establish how many moving objects we can perceive simultaneously.

Studies that have investigated this issue have used transparent-motion stimuli and have found two main findings. The first is that there is an initial limit that is determined by the signal-to-noise level of the stimulus. Specifically, if the different motion signals are determined purely by direction differences, then only two signals can be simultaneously perceived (Edwards & Greenwood, 2005; Mulligan, 1992). This transparency limit is due to the high signal levels required to perceive motion transparency. Edwards and Greenwood used a modified global-motion stimulus (Newsome & Pare, 1988) in which the signal intensity is determined by the ratio of signal (dots moving in the signal direction) to noise (dots moving in all other directions) dots. They found that while the perception of unidirectional motion was possible at signal intensities of around 10–15%, the perception of bi-directional motion required intensities of around 40%. Given that dots moving in one signal direction act as noise for the other signal directions (Edwards & Nishida, 1999), this means that the maximum signal intensity when three signal directions are presented (and they all drive the same global-motion system) is only 33%, hence accounting for the limit of two.

Independent global-motion systems tuned to speed and depth exist (Edwards, Badcock, & Smith, 1998; Hibbard & Bradshaw, 1999; van Boxtel & Erkelens, 2006) meaning that, for example, dots moving in a near depth-plane do not affect the extraction of a global-motion signal from dots moving in a far depth-plane. Hence the effective signal intensity in each signal direction can be increased if some of them drive different global-motion systems. That is, if the different signals differ not just in direction, but also in speed and/or depth. Doing this allows the transparency limit to be increased to three, but not any higher (Greenwood &

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Edwards, 2006a, 2006b). Thus, there appears to be a higher-order limit, independent of the signal to noise imposed one, that restricts the simultaneous perception of motion transparency to three.

Of course, we seldom encounter visual scenes that contain three transparent motion-signals, let alone more than that. Instead of multiple transparent signals, it is more common to encounter many moving objects, i.e. the movement of multiple spatially-localised and segmented stimuli. For example, cars in busy traffic, people on a crowded street or (from an evolutionary perspective) a herd of wildebeest on an African plain. So it is possible that the limit of three is specific to the processing of transparent motion-signals. Note that while a limit of three has also been found with non-transparent global-motion signals, specifically with global-motion signals in spatially contiguous regions, performance in that condition may have been limited by signal-to-noise issues (Greenwood & Edwards, 2009).

Consequently, the aims of the present study were to determine the maximum number of motion signals that can be simultaneously perceived with spatially-localised stimuli and to what extent signal-to-noise levels also play a role in the processing of these stimuli.

In relation to the question of signal-to-noise levels, a potential relevant issue is how the spatially localised stimuli are processed, specifically, whether they are processed by either the standard motion-system or by what appears to be a form-specific system (Edwards, 2009). The claim of a form-specific system, that is different from the standard motion-system, is based upon differences in how luminance-polarity and colour (red/green) information are pooled when processing different types of stimuli. In the standard motion-system, luminance-polarity and colour information are pooled by a common system (Edwards & Badcock, 1994, 1996; Murray, Sekuler, & Bennett, 2003; Snowden & Edmunds, 1999). This is different to the processing of static form-information, in which luminance polarity information appears to be processed by two independent systems, i.e. light and dark form signals are pooled by separate global-form systems (Badcock, Clifford, & Khuu, 2005; Wenderoth, 1996; Wilson, Switkes, & De Valois, 2004). Similar selective pooling is observed in motion processing when the signal dots are locally arranged into particular patterns. For example, when four signal-dots are arranged into a square pattern, luminance polarity and colour information also appears to be pooled via independent mechanisms, but not when they are arranged in random, locally-grouped, shapes (Edwards, 2009; Edwards, Coningham, & Rae-Hodgson, 2011). Why have different systems that pool the various signals differently? In the processing of information about objects (forms), segmentation and pooling are two sides of the same coin, and given that luminance polarity and colour are typically good segmentation cues, independent pooling of those signals improves the visual system's ability to segment and efficiently process discrete objects. Conversely, optic-flow information is generated by all objects in the visual scene, so the visual system would not want to segment out any objects in the scene when processing an optic-flow signal. Hence a single, common system is used (Edwards, 2009). This putative form-specific system appears to be more sensitive to motion than the standard system. In the study by Edwards (2009) the number of signal dots was fixed, so thresholds were established by varying the number of noise dots: the higher the number, the lower the signal-to-noise level so the more sensitive the system. When the signal dots were in a square arrangement (and, based upon the findings of independent pooling of luminance polarity and colour information, drove the form-specific system) thresholds were twice those than when they were arranged in a random pattern (and drove the standard system), e.g. 230 versus 110 noise dots. Other studies have also found that the spatial arrangement of the dots affects global-motion thresholds (Verghese, McKee, & Grzywacz, 2000).

Thus, if signal-to-noise levels are important in determining the maximum number of motion signals that can be simultaneously perceived with spatially-localised stimuli, it may be possible to perceive more than the previously observed limit of three only with stimuli that drive the form-specific system.

2. Experiment 1: perception limits for spatially localised stimuli

The aim of this study was to determine how many motion signals could be simultaneously perceived using spatially-localised stimuli that drove either the form-specific or standard motion-systems (Edwards, 2009).

3. Method

3.1. Observers

Four observers were used, one of the authors (RR) and three others who were naïve with respect to the aims of the study. All had normal or corrected to normal acuity.

3.2. Apparatus

Stimuli were presented on a Phillips Brilliance 202P4 cathode-ray-tube monitor which was driven by a Cambridge Research Systems VSG 2/5 graphics card in a host Pentium computer. The monitor had a spatial resolution of 1024×768 pixels and a frame rate of 100 Hz.

3.3. Stimuli and procedure

Modified versions of the stimulus used by Edwards (2009) were employed. Each signal direction was defined by four dots that were arranged in either a square pattern, to drive the form-specific motion system, or a variable pattern, to drive the standard motion system. The square patterns were formed by selecting the location of the first dot to ensure that it could move over the three motion frames without moving beyond the spatial extent of the viewing aperture. The remaining dots were offset horizontally and vertically by 0.34° to form a square pattern. The variable patterns were generated in the same manner, but the angle of the offset of each dot was randomized over the full 360°. This resulted in groupings of the four dots that had the same average spatial proximity as those in the Square condition, and hence the same spatial-frequency content (Edwards, 2009) but with random shapes.

A temporal two-alternative forced-choice procedure was used. Each interval contained either n or $n + 1$ signal groups and the total number of dots was kept constant at 60. The observer's task was to indicate which interval contained the highest number of signal directions. All dots started off in the same 4 dot pattern, e.g. 15 separate squares in the Square Condition, or 15 different random patterns in the Variable Condition. Those patterns composed of signal dots kept their shape as they moved, given that each dot making up that pattern moved in the same direction on each motion-frame transition, while those patterns composed of noise dots fell apart as the noise dots moved in random directions on each motion-frame transition. Each motion sequence consisted of three image frames, with each frame being presented for 50 ms. A typical motion sequence for the Square Condition is shown in Fig. 1. The directions that each signal group moved in were randomly chosen from eight directions: the four cardinal directions and the four diagonals. While no two signal groups could move in the same direction, the direction of the noise dots was unconstrained. That is, they could move in any direction over the full 360°.

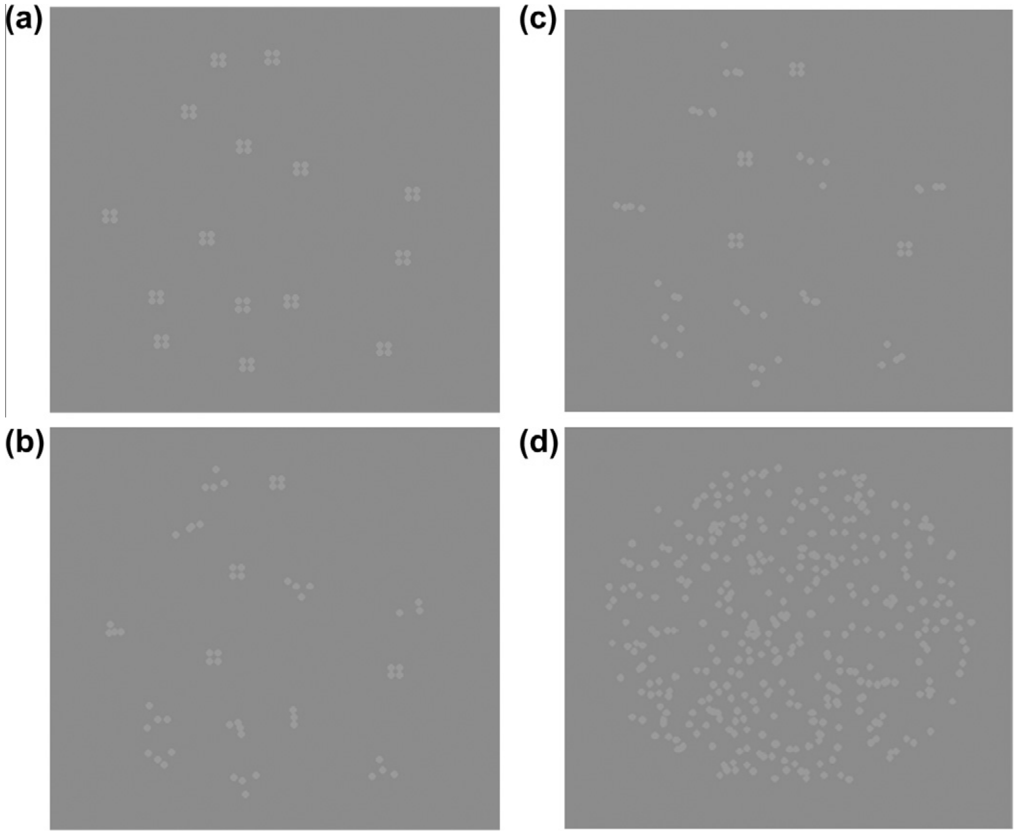

Fig. 1. An example of the stimuli used in Square Condition in Experiment 1. The images in three-frame motion sequence are shown in (a) to (c), with a signal level of 4. An example of the mask is shown in (d).

To prevent observers using just the static image in the last motion frame in each sequence to perform the task, a mask frame was presented at the end of each motion sequence. The mask consisted of 300 randomly assigned dots and was presented for 240 ms. Without this mask, observers could make the discrimination when each interval consisted of only the last frame in each sequence (presented for 100 ms), but they could not when the mask was included. The comparisons ranged between 0 versus 1 and 4 versus 5, though given the results for the Square Condition, this condition was also tested on the range 2 versus 3 to 6 versus 7.

The background had a mean luminance of 62 cd/m^2, and the dots had a positive Weber contrast of 20% and were 0.25° in diameter. The dots were displaced by 0.32° on each frame transition resulting in a speed of 6.4°/s and were presented in circular aperture with a diameter of 20°. The observer sat 50 cm from the monitor, with their head supported on a chin rest.

4. Results and discussion

The results for the four observers are shown in Fig. 2. Performance, percentage of the trials the observer got correct, is plotted against the comparison level. Given that a 2AFC was used, threshold performance was set at 75%. The pattern of results is the same for all observers. For the Variable Condition, only comparisons up to the 1 versus 2 level were at or above 75% (i.e. the 75% level fell within or below the 95% confidence intervals around the observer's performance level) meaning that the observers could only detect a single motion signal. For the Square Condition, comparisons up to the 4 versus 5 level were at or above the 75% level (Fig. 2b). When the range was extended, only comparisons up to the 5 versus 6 level were at or above 75% (Fig. 2c). This means that observers could perceive five motion signals simultaneously in the Square Condition.

These results indicate that it is possible to perceive more than the previously observed limit of three motion directions simultaneously (Edwards & Greenwood, 2005; Greenwood & Edwards, 2006a, 2006b, 2007, 2009), but only when the stimuli drive the form-specific motion system. One potential reason for this difference is the different sensitivities of the two systems to signal-to-noise levels. It has been shown that the form-specific system is able to detect motion signals when a greater number of noise dots are present, as compared to the standard motion system (Edwards, 2009). That is, it requires lower signal levels in order to detect motion. Given that one of the limitations to the detection of multiple motion signals is the higher signal levels required for detecting multiple, as compared to single, motion directions (Edwards & Greenwood, 2005) it is possible that the greater sensitivity of the form-specific system to signal intensity allows it to simultaneously detect a greater number of directions. The next experiment investigates the role of signal-to-noise levels in more detail.

5. Experiment 2: influence of signal-to-noise levels

Experiment 1 showed that using spatially-localised stimuli that drive the form-specific system (Square Condition) can result in a simultaneous motion-perception limit that exceeds the limit previously obtained with transparent stimuli, i.e. a limit of 5 compared to 3 (Greenwood & Edwards, 2006a, 2006b). Further, the limit obtained for spatially-localised stimuli that drive the standard system (Variable Condition) was only 1, i.e. only unidirectional motion could be perceived. Several questions follow from these findings. Specifically: Why is the limit greater for the form-specific system

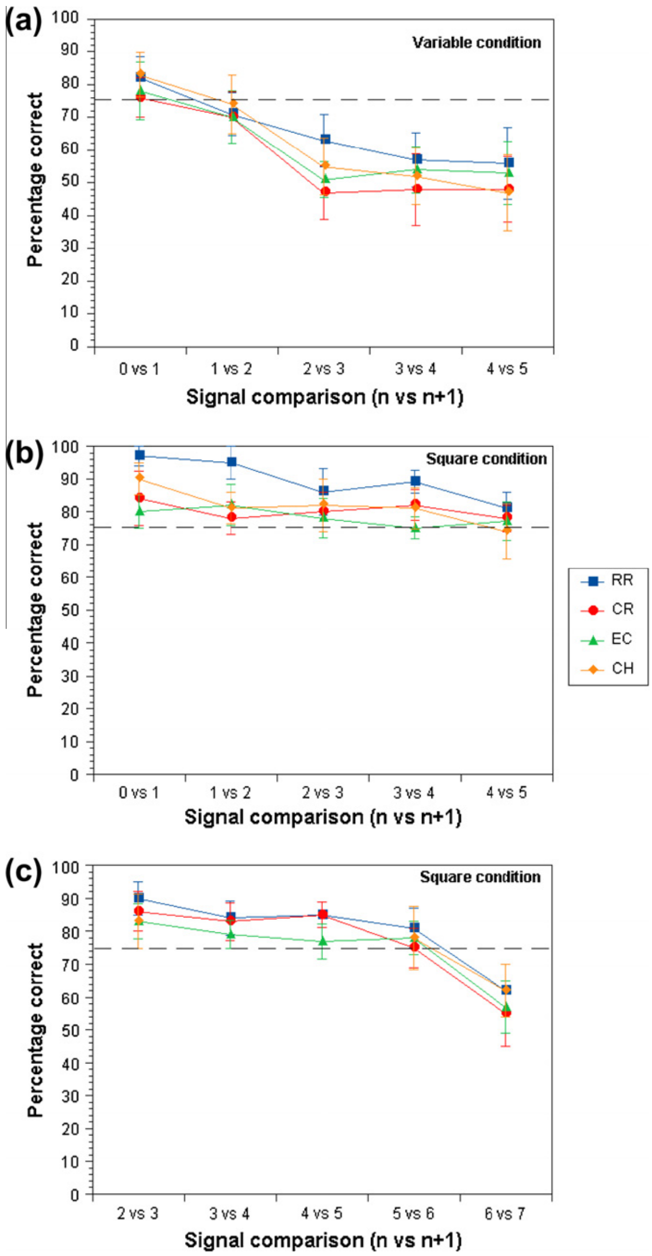

Fig. 2. Results for Experiment 1. The performance (percentage of responses that were correct) is plotted against the signal comparison level (n versus $n + 1$). Error bars indicate 95% confidence intervals. (a) Results for the Variable Condition, (b and c) results for the Square Conditions over two different comparison ranges.

than the standard system? Why was the limit for the standard system only 1? and Is the limit for the form-specific system fixed at 5?

Answers to these questions potentially depend upon whether signal-to-noise levels play a role in influencing the simultaneity limit for spatially localised stimuli. We know that for multiple transparent-motion signals, signal-to-noise levels impose an initial limitation on the number of signals that can be simultaneously perceived. Increasing the signal-to-noise level, by having the different signals drive different global-motion systems can increase the simultaneity limit for transparent motion from 2 to 3 (Greenwood & Edwards, 2006a, 2006b). We also know that the form-specific system is more sensitive to signal-to-noise levels than the standard motion system (Edwards, 2009). Hence, if signal-to-noise levels and sensitivity to those levels play a role in the perception of multiple, spatially-localised signals, then it is possible that, in Experiment 1, the form-specific system may have been sensitive to a higher number of signals because it was sensitive to low signal-to-noise levels, and that the standard system may have only been sensitive to unidirectional motion due to the too low (for that system) signal-to-noise levels.

The current experiment investigated this possibility by determining if simultaneous motion-limits for the two systems depend upon the signal-to-noise levels when spatially localised motion signals are used. Specifically, we sought to determine whether increasing or decreasing the signal-to-noise limit in the stimuli driving the form-specific system would decrease or increase, respectively, the simultaneous motion-limit for it, and whether increasing the signal-to-noise limit in the stimuli driving the standard system would increase its limit.

Additionally, we wanted to investigate any potential effect of another difference between the two stimuli used in Experiment 1. Having an unchanging shape across all trials in the Square Condition and changing the shapes in the Variable Condition may have made it possible to employ selective attention in the former but not in the latter condition (Laarni & Häkkinen, 1994; Lambert & Hockey, 1986). While this seemed unlikely to have affected the results, given that we have (unpublished) data from our laboratory that shows using the same 'variable' shape in all trials resulted in the same motion thresholds as for the standard Variable Condition (for uni-directional motion detection) the current experiment tested for this possibility by using a Fixed Condition to drive the standard motion-system. This condition used a shape that was similar to the ones produced in the Variable Condition in Experiment 1, but it was used in all of the trials in this experiment. See Fig. 3.

6. Method

6.1. Observers

Two of the observers from Experiment 1 were used.

6.2. Stimuli and procedure

The stimuli and procedure were the same as used in Experiment 1 except that the total number of dots were varied. For the Square Condition, total dot-numbers of 40 and 80 were used, compared to 60 in Experiment 1. For the Fixed Condition, the number of dots was varied between 28 and 60.

7. Results and discussion

The results are shown in Fig. 4 with the patterns being the same for both observers. For the Square Condition, increasing the number of dots to 80 resulted in the observers being able to perform at threshold levels for comparisons only up to 4 versus 5 (Fig. 4a). That is, their threshold was 4, as opposed to the threshold of 5 obtained with the 60 dots used in Experiment 1. On the other hand, decreasing the number of dots to 40 resulted in observers

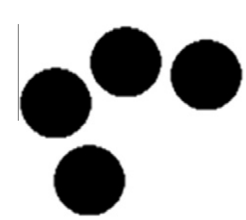

Fig. 3. The spatial arrangement of the dots used in the Fixed Condition in Experiment 2.

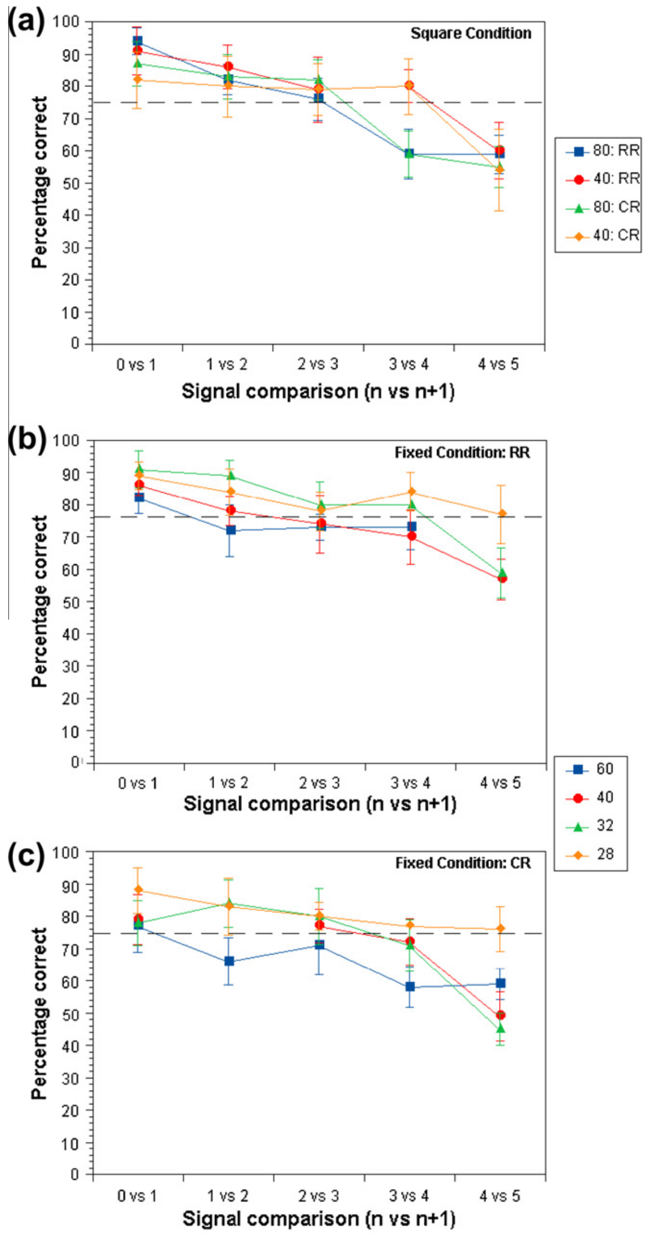

Fig. 4. Results for Experiment 2. The performance (percentage of responses that were correct) is plotted against the signal comparison level (n versus $n + 1$). Error bars indicate 95% confidence intervals. (a) Results for the Square Condition for two observers (RR and CR) at two total dot numbers (40 and 80), (b and c) results for the Fixed Conditions for the two observers over a range of dot numbers (80–28).

being able to do comparisons up to 6 versus 7, i.e. a threshold of 6. For the Fixed Condition, decreasing the number of dots improved performance (Fig.4b and c). At the lowest dot number (28), both observers could successfully perform at the 4 versus 5 level, showing they could detect at least 4 signals simultaneously. This observation needs to be qualified, however, because it is possible that the nature of the task changed when only 28 dots were used. With 28 total dots, there were 7 groups of 4 dots, meaning that in the 4 versus 5 comparison, there were more signal than noise groups: 3 and 2, respectively. While neither observer had the impression of doing so, it is possible that they based their performance on the perception of the fewer number of noise dots in the 5 signal condition. Note also, if that was their technique in this condition, they were unable to employ this technique in the Square Condition with 40 dots (10 groups of 4 dots) in the 7 versus 8 (3 and 2 noise groups, respectively). Though, while that condition had the same number of noise groups, it did have more signal groups.

Finally, in the Fixed Condition at the 60 dot level (the same number of dots used in Experiment 1) neither observer could process more than 1 signal, which is the same performance as observed in Experiment 1 for the Variable Condition with 60 dots. This finding indicates that allowing the observer to know what shape the signal dots would be in, and hence the potential use of selective attention (Laarni & Häkkinen, 1994; Lambert & Hockey, 1986) did not, in and of itself, affect performance. We would argue that performance improves only when those shapes are processed by the form-specific system.

Taken as a whole, these results indicate that signal-to-noise levels play a role in influencing simultaneous motion-perception limits with spatially-localised stimuli, for both the form-specific and standard motion-systems and that cueing the observer to the shape of the stimulus does not affect performance – at least when performance is mediated by the standard motion-system.

8. General discussion

The main findings from the present study are that it is possible to perceive more than 3 motion signals simultaneously with spatially-localised stimuli, and that the limit depends upon the signal-to-noise levels in the stimulus. With stimuli that drive the form-specific system (Square Condition), up to 6 directions could be perceived (Experiment 2) but this was reduced to 4 when the number of noise dots was increased (Experiment 2). With stimuli that drive the standard motion system (Variable and the Fixed Conditions) only 1 direction could be perceived at signal levels for which 5 could be perceived with the Square Condition (Experiments 1 and 2) but this was increased to at least 3, when the number of noise dots was decreased (Experiment 2).

There are a number of implications from these results. The first is that the previously observed limit of 3 (Greenwood & Edwards, 2006a, 2006b) seems to only apply to the processing of transparent stimuli, and not to the spatially-localised stimuli used in the current study. That a higher limit would exist for the motion of spatially-localised signals (i.e. objects) is consistent with ecological considerations. We seldom encounter 3 or more transparent signals simultaneously, while more than 3 moving objects in a visual scene is common. While more than 3 signals can be simultaneously perceived, there does not appear to be a fixed upper limit, like there is with the perception of transparent motion. Signal-to-noise levels, and the system's sensitivity to those levels appear to be the only limiting factors, at least up to the number of signals tested in the current study. This signal-to-noise dependency also means that the form-specific system has a much higher simultaneity limit than the standard system, given its greater sensitivity (Edwards, 2009). Under the same conditions, the form-specific system could detect 5 signals, compared to 1 for the standard system. This greater ability of the form-specific system to simultaneously process multiple motion signals could be the main reason for its existence, and the marked difference in the performance for the two types of stimuli provides further support for the actual existence of a form-specific system.

Additionally, the ability of the form-specific system to independently process both light and dark, and red and green signals (Edwards, 2009; Edwards, Coningham, & Rae-Hodgson, 2011) may make the next stage in the processing of multiple motion signals, i.e. sequential processing, easier. That is, in scenes in which the number of motion signals exceed the system's simultaneity-limit, the visual system would then have to process subsets of these signals sequentially. The selection of these subsets would likely involve the allocation of selective attention. Attention can be allocated to different locations within the visual scene (space-based attention) or to different objects (object-based attention) (Eriksen & St James, 1986; Friedman-Hill & Wolfe, 1995; Kahneman, Treisman, & Gibbs, 2004). So, if the ability to independently pool light and dark, and red and green motion signals that has been observed in the processing of unidirectional motion signals (Edwards, 2009; Edwards, Coningham, & Rae-Hodgson, 2011) is maintained in the processing of multiple motion signals, then that would potentially allow object-based segmentation and hence easier sequential processing with stimuli processed by the form-specific system. We are currently investigating this issue. Note, it is also not clear what types of stimuli are actually processed by the form-specific system, that is, which stimulus properties determine whether it is processed by just the standard system or both it and the form-specific system. We are also investigating that issue. Also, while the current study shows the ability of observers to do a discrimination based upon the number of signals in a two motion sequences, it does not reveal how much information they encode about those motion signals (Shooner et al., 2010). We are currently investigating this issue by presenting a single motion sequence, and requiring observers to indicate how many motion signals are contained in the sequence, the actual directions, and what direction a post-cued signal group had moved in. Of relevance to the current study, when tested in this manner, observers are able to perceive more than 3 motion signals.

Finally, findings from the multiple-object-tracking literature suggest that the maximum number of objects that can be tracked is around 4, unless their speed is particularly slow, in which case up to 8 objects can be tracked. (Alvarez & Franconeri, 2007; Pylyshyn & Storm, 1988). However, in these studies, stimuli are presented for extended duration (7 s or more) so the extent to which performance reflects simultaneous or sequential processing is not clear. This is reflected in the current debate over the mechanism of multiple object tracking. Some theories suggest simultaneous processing occurs, e.g. the FINST model (Pylyshyn, 1989) while other offer a sequential account (d'Avossa et al., 2006; ; Oksama & Hyönä, 2008). Note also, the markedly different performance for the Square (form-specific system) and Variable and Fixed (standard system) Conditions indicates that in the current study, observers were not just engaged in object tracking.

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